Ionization history of the Universe as a test for Super Heavy Dark Matter particles

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In this paper we discuss the possible distortions of the ionization history of the universe caused by an injection of nonthermal energy due to decays of hypothetical Super Heavy Dark Matter (SHDM) particles. These particles are usually considered as a possible source of Ultra High Energy Cosmic Rays (UHECRs) in the framework of the Top-Down model. Estimates of fraction of energy of decays converted to the UV range show that, for suitable parameters of SHDM particles, the significant distortions of power spectra of CMB anisotropy appear. Comparison with the observed power spectrum allows to restrict some properties of the SHDM particles. These decays can also increase of about 5 – 10 times the degree of ionization of hydrogen at redshifts $z \sim 10 - 50$ that essentially accelerates the formation of molecules H_2 and first stars during "dark ages".

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I. INTRODUCTION

Two different approaches to investigation of the general physical properties of the cosmological expansion of the Universe are now in the fast progress. One of them is theoretical and experimental investigations of the Cosmic Microwave Background (CMB) anisotropy and polarization. Other is the investigation of possible manifestations of Super Heavy Dark Matter (SHDM) particles several kinds of which can be created at the period of inflation of the Universe.

The analysis of the CMB anisotropy and polarization is the "gold mine" for the determination of cosmological parameters such as fractions of baryons (Ω_b), cold dark matter(Ω_m) and vaccua (Ω_Λ), Hubble constant $h = H_0/100$ km/s/Mpc, power index n of initial adiabatic (or isocurvature) perturbation, possible redshifts of reionization z_{ion} and so on. Recent progress in this direction is based on unique information about the power spectrum of CMB anisotropy measured in the ground and balloon-borne experiments such as BOOMERANG [1] and MAXIMA-1 [2]. It is generally believed that future high precision observations of the CMB anisotropy allow to test the most important predictions of the modern theories of inflation and will stimulate a further study of the very early Universe.

On the other hand, recent observations of AGASA [3], Fly's Eye [4] and Haverah Park [5], demonstrate the existence of the Ultra – High Energy Cosmic Rays (UHECR) with energy above the Greisen-Zatsepin-Kuzmin (GZK) [6,7] cutoff, $E_{GZK} \sim 10^{20}$ eV, that is one of the most intriguing mysteries of the modern physics and astrophysics (see reviews [8,9]). As was suggested by Berezinsky, Kachelrieß and Vilenkin [10] (see also [11]), the formation of such UHECRs can be related to decays of the various kinds of SHDM X–particles with masses $M_X \geq 10^{12}$ GeV in the framework of the so-called Top-Down scenario of the UHECR creation. (Below we denote by X all possible types of SHDM).

As is commonly believed, decays of SHDM particles into the high energy protons, photons, electron-positron pairs and neutrinos occurs through the production of quark-antiquark pairs ($X \to q, \overline{q}$), which rapidly hadronize, generate two jets and transform the energy into hadrons (ω_h ∼5%) and pions ($1 - \omega_h$ ∼95%) [12]. It can be expected that later on the energy is transformed mainly to high energy photons and neutrinos. This means that, for such decays of SHDM particles with 10^{12}GeV $< M_X < 10^{19}$ GeV, the UHECR with energies $E > 10^{20}$ eV are dominated by photons and neutrinos [12].

However, recent observations Ave et al. [13] shown that above 10^{19}eV less than 50% of the primary cosmic rays can be photons. These observations demonstrate that probably only some part of the observed UHECR can be related to the decays of the SHDM particles, and more sensitive and refined methods must be used for further observational investigation of such X–particles.

In this paper we discuss the possible distortions of the ionization history of the primeval plasma at $z \sim 10^3$ caused by the energy injection due to decays of the SHDM particles. Comparison of expected distortions with already available observational BOOMERANG and MAXIMA-1 data allows us to restrict more strongly the rate of decays of the possible SHDM particles and, at the same time, to refine evaluations of possible distortions of CMB anisotropy and polarization. We show also that, for reasonable parameters of the SHDM particles, their decays can increase of about 5 – 10 times the degree of ionization of hydrogen at redshifts $z \sim 10 - 50$ that essentially accelerates the formation of molecules H_2 and first stars during "dark ages".

The paper is organized as follows. In section 2 some information about of the SHDM particles is summarized. In section 3 the spectrum of UV radiation produced by the energy injection is found. In sections 4 and 5 we discuss the delay of cosmological recombination and the hydrogen ionization history. Main results are discussed in section 6.

II. EXPECTED FLUX OF HIGH ENERGY PHOTONS

The expected domination of products of decay of the X-particle by the high energy pions, neutrino and photons follows from quite general arguments. Probable energy losses of neutrinos are small [8], but at high redshifts the interaction of high energy photons with the CMB background leads to formation of electromagnetic cascades. At small redshifts the efficiency of this interaction decreases and the evolution of such photons depends upon unknown factors such as the extragalactic magnetic field and properties of radio background.

Summarizing available information about the photon component of UHECRs Bhattacharjee and Sigl [8] estimate the spectrum of injected photons for a decay of a single X-particle as follows:

$$\frac{dN_{inj}}{dE_\gamma} = \frac{0.6(2-\alpha)}{M_X}\frac{f_\pi}{0.9}\left(\frac{2E_\gamma}{M_X}\right)^{-\alpha},\; E_\gamma \le \frac{M_X}{2} \tag{1}$$

where f_π is the fraction of the total energy of the jet carried by pions (total pion fraction in terms of of number of particles), $0 < \alpha < 2$ is the power index of the injected spectrum, M_X is the mass of the SHDM particles. For the photons path length $l_\gamma \sim 1-10$Mpc at $E_\gamma \sim E_{GZK}$ in respect to the electron-positron par creation on the extragalactic radio background (see [8,15]) we get for the photon flux $j_{inj}(E_\gamma)$ at the observed energy E_γ:

$$j_{inj}(E_\gamma) \simeq \frac{1}{4\pi} l_\gamma(E_\gamma)\dot{n}_X \frac{dN_{inj}}{dE_\gamma} \tag{2}$$

where $\dot{n}_X$ is the decay rate of the X - particles. For the future calculation we will use the normalization of $j_{inj}(E_\gamma)$ on the observed UHECR flux which corresponds to normalization of the decay rate $\dot{n}_X$ at present time, $t = t_u$, [8]:

$$\dot{n}_{X,0} \simeq 10^{-46}\mathrm{cm}^{-3}\mathrm{s}^{-1} M_{16}^{1-\alpha}\Theta_X, \tag{3}$$

$$\Theta_X \approx \frac{10\mathrm{Mpc}}{l_\gamma(E_{obs})}\frac{E_{obs}^2 j_{obs}(E_{obs})}{1\mathrm{eVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}}(2E_{16})^{\alpha-3/2}\frac{0.5}{2-\alpha}\frac{0.9}{f_\pi}$$

where $M_{16} = M_X/10^{16}$GeV, $E_{16} = E_{obs}/10^{16}$GeV, E_{obs} and $j_{obs}(E_{obs})$ are the observed energy and flux of the UHECR. Normalization (3) does not depend on the nature of the X-particles. The precision achieved is about of order of magnitude.

At $z \gg 1, t \ll t_u$ the decay rate depends on the physical nature of the X− particles (see, for example, [8]). To reconstruct the ionization history of the universe at redshifts $z \sim 10^3$ we will consider the simplest evolutionary model with:

$$\frac{dn_X(t)}{dt} + 3H(t)n_X(t) = -\frac{n_X(t)}{\tau_X} \tag{4}$$

$$n_X(t) = n_{X,0}(1+z)^3 \exp\left(\frac{-(t-t_u)}{\tau_X}\right), \tag{5}$$

where $H(t)$ is the Hubble parameter, z is a redshift, $t_u \sim H^{-1}(z=0)$ is the age of the universe, $n_X(t)$ and τ_X are the number density and life time of the X-particles. In a general case, we can write

$$\dot{n}_X = \frac{n_X(z)}{\tau_X} = \dot{n}_{X,0}(1+z)^3\Theta_\tau(z), \quad \Theta_\tau(z) \ge 1, \tag{6}$$

For $\tau_X \ge t_u$, $\Theta_\tau \approx 1$ and the decay rate, $\dot{n}_X$, varies only due to the general expansion.

III. ELECTROMAGNETIC CASCADES AT THE PERIOD OF THE HYDROGEN RECOMBINATION.

To evaluate the distortions of the power spectra of CMB anisotropy and polarization we need firstly to consider the transformation of high energy injected particles to UV photons influenced directly the recombination process. The electromagnetic cascades are initiated by the ultra high energy jets and composed by photons, protons, electron- positrons and neutrino. At high redshifts, the cascades develops very rapidly via interaction with the CMB photons and pair creation ($\gamma_{UHECR} + \gamma_{CMB} \to e^+ + e^-$), proton-photon pair production ($p_{UHECR} + \gamma_{CMB} \to p^{'} + \gamma' + e^+ + e^-$), inverse Compton scattering ($e^-_{UHECR} + \gamma_{CMB} \to e^{'} + \gamma^{'}$), pair creation ($e^-_{UHECR} + \gamma_{CMB} \to e^{'} + e^- + e^+ + \gamma^{'}$), and, for neutrino, electron- positron pair creation through the Z-resonance. As was shown by Berezinsky et al. [16] and Protheroe et al. [17], these processes result in the universal normalized spectrum of the cascade with a primary energy E_γ:

$$N_\gamma(E) = \frac{E_\gamma E^{-2}}{2+\ln(E_c/E_a)}\begin{cases}\sqrt{\frac{E}{E_a}} & E \le E_a \\ 1 & E_a \le E \le E_c \\ 0 & E_c \le E\end{cases} \tag{7}$$

$$\int_0^{E_\gamma} E N_\gamma dE = E_\gamma$$

where $E_c \simeq 4.6 \cdot 10^4 (1+z)^{-1}$GeV, $E_a = 1.8 \cdot 10^3 (1+z)^{-1}$GeV. At the period of recombination $z \sim 10^3$ and for lesser redshifts both energies, E_a and E_c are larger then the limit of the electron-positron pair production $E_{e^+,e^-} = 2m_e = 1$ MeV and the spectrum (7) describes both the energy distribution at $E \geq E_{e^+,e^-}$ and the injection of UV photons with $E \ll E_{e^+,e^-}$. However, the spectrum of these UV photons is distorted due to the interaction of photons with the hydrogen - helium plasma.

In the range of less energy of photons, $E \leq 2m_e$, and at higher redshifts, $z \geq 10^4$, when equilibrium concentrations of HI, HeI and $HeII$ are small and their influence is negligible, the evolution of the spectrum of ultraviolet photons, $N_{uv}(E,z)$, occurs due to the injection of new UV photons and their redshift and Compton scattering. It is described by the transport equation [17]

$$\frac{\partial N_{uv}}{\partial z} - \frac{3N_{uv}}{1+z} + \frac{\partial}{\partial E}\left(N_{uv}\frac{dE}{dz}\right) + \frac{Q(E,z)}{(1+z)H} = 0, \quad (8)$$

$$\frac{1}{E}\frac{dE}{dz} = \frac{1}{1+z} + \frac{c\sigma_T n_e}{(1+z)H(z)}\left(\frac{E}{m_e c^2}\right) = \frac{1+\beta_\gamma(E,z)}{1+z}$$

$$Q(E,t) = \dot{n}_X \int dE_\gamma N_\gamma(E,E_\gamma)\frac{dN_{inj}}{dE_\gamma} = \dot{n}_X N_\gamma(E,M_X)$$

where the Hubble parameter is

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + 1 - \Omega_m},$$

σ_T is the Thomson cross-section, $n_e \propto (1+z)^3$ is the number density of electrons and, so, $\beta_\gamma \propto (1+z)^{3/2}E$. Here $Q(E,t)$ is considered as an external source of UV radiation.

The general solution of equation (8) is:

$$N_{uv}(z) = \int_z^{z_{mx}} \frac{Q(x)}{H(x)}\frac{E^2(x)}{E^2(z)}\left(\frac{1+z}{1+x}\right)^4 \frac{dx}{1+x}, \quad (9)$$

$$\frac{E(x)}{E(z)} = \frac{1+x}{1+z}\left(1 - \frac{2}{5}\beta_\gamma(E,z)\left[\left(\frac{1+x}{1+z}\right)^{5/2} - 1\right]\right)^{-1}$$

where the maximal redshift, z_{mx}, in (9) is defined by the condition $E(x) = 2m_e c^2$.

As is seen from (9), the Compton scattering dominates for $E \gg 30$keV, when

$$\beta_\gamma(E,z) = 44\frac{E}{m_e c^2}\sqrt{\frac{0.3}{\Omega_m}\frac{h\Omega_b}{0.02}}\left(\frac{1+z}{10^3}\right)^{3/2} \gg 1, \quad (10)$$

$$N_{uv}(z) \propto \frac{\dot{n}_X(z)N_\gamma(E,M_X)}{H(z)\beta_\gamma(E,z)} \propto \frac{\sqrt{1+z}\,\Theta_\tau(z)}{E^{5/2}}, \quad (11)$$

For the most interesting energy range, $E \ll 30$keV, $\beta_\gamma(E,z) \ll 1$, we get again

$$N_{uv}(E(z),z) \approx \frac{2}{3}\frac{\dot{n}_X(z)}{H(z)}N_\gamma(E,M_X). \quad (12)$$

The energy density, $\Delta\epsilon$, produced by the decays at redshifts $z \geq 10^3$ near the energy of ionization of hydrogen and helium, $E \simeq I_H$, is

$$\Delta\epsilon = \int_{I_H}^{E} E N_{uv}(E)dE \approx \kappa_H \frac{\dot{n}_X M_X}{H(z)}\left(\sqrt{\frac{E}{I_H}} - 1\right), \quad (13)$$

$$\kappa_H \approx \frac{4}{3}\frac{1}{2+\ln(E_c/E_a)}\sqrt{\frac{I_H}{E_a}} \approx 2.2\cdot 10^{-5}\sqrt{\frac{1+z}{10^3}},$$

$$\frac{\dot{n}_X M_X}{H(z)\Theta_X} \approx 25\frac{eV}{cm^3}\left(\frac{z}{10^3}\right)^{3/2}\sqrt{\frac{0.15}{\Omega_m h^2}}\left(\frac{M_X}{10^{16}\mathrm{GeV}}\right)^{2-\alpha}\Theta_\tau.$$

where $I_H = 13.54$ eV is the potential of ionization of hydrogen. For comparison, the energy density of the CMB radiation at $z = 10^3$, $T_\gamma = 2700(1+z)K$ and $E \geq I_H$ is

$$\Delta\epsilon_{bb} \approx 4\cdot 10^{-6}\left(\frac{1+z}{10^3}\right)\exp\left[58.5\left(1 - \frac{10^3}{1+z}\right)\right]\frac{eV}{cm^3},$$

that demonstrates the possible strong influence of decays for the recombination history.

IV. DISTORTIONS OF THE CMB ANISOTROPY AND POLARIZATION.

The spectrum (12) gives a reasonable description of the cascade at higher redshifts, $z \geq 10^4$, when the concentrations of neutral hydrogen and helium are small. At redshifts $z \leq 10^3$ and for $E \simeq I_H$ the spectrum (12) is strongly distorted due to the reionization of hydrogen and helium, and the main part of energy (13) is rapidly converted to the resonance lines, namely, $Ly{-}c = 912\mathring{A}$, & $228\mathring{A}$ and $Ly{-}\alpha = 1216\mathring{A}$, & $304\mathring{A}$. To estimate in the case the distortions of the CMB power spectrum, we can use the approach proposed in [18] and write the rate of production of resonance and ionized photons, $\dot{n}_r$, as follows:

$$\frac{1}{\langle n_b(z)\rangle}\frac{dn_r}{dt} = \int_{I_H}^{E} Q(E,z)dE = \varepsilon(z)H(z) \quad (14)$$

$$\varepsilon(z) \approx \frac{2}{2+\ln(E_c/E_a)}\frac{M_X}{\sqrt{I_H E_a}}\frac{\dot{n}_X}{H(z)\langle n_b(z)\rangle}$$

The direct comparison (13) and (14) shows that

$$\varepsilon(z) \sim 1.5\frac{\Delta\epsilon(4I_H)}{I_H\langle n_b(z)\rangle},$$

that demonstrates the domination of directly injected UV photons at $E \sim I_H$. These photons decelerate the process of hydrogen recombination and slightly decrease the redshift of recombination. On the contrary, the moderate growth of concentration of the Ly-α photons as compared with their concentration in the CMB is not so important. This inference is a natural consequence of the direct generation of Ly-c photons in the cascades considered in Secs. II and III and is confirmed by numerical simulations.

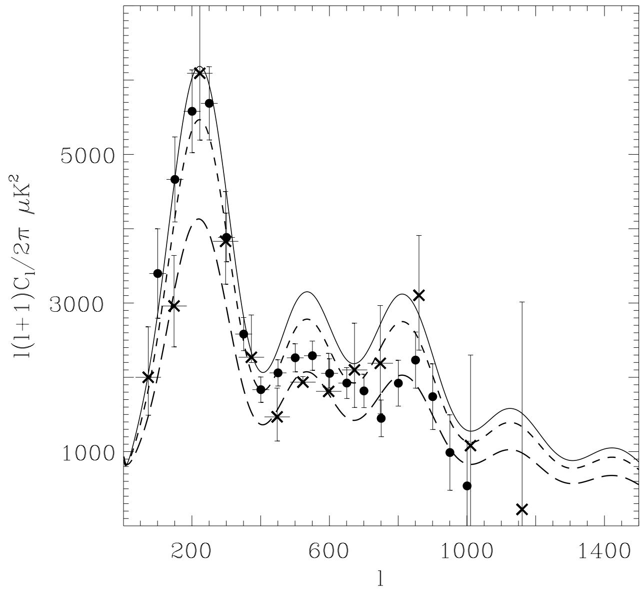

FIG. 1. The power spectra of CMB anisotropy, $l(l+1)C_l/4\pi$, vs. l are plotted for the standard model, ($\varepsilon = 0$, solid line), and for models with $\varepsilon = 2/(1+z)$, (dashed line), and $\varepsilon = 3/(1+z)$, (long dashed line). Observational data are plotted by points (BOOMERANG) and crosses (MAXIMA-1).

For the mean number density of baryons

$$\langle n_b \rangle \approx 240 \frac{\Omega_b h^2}{0.02} \left(\frac{1+z}{10^3} \right)^3 ,$$

we have

$$\varepsilon(z) \approx \frac{2.5 \cdot 10^{-4}}{1+z} M_{16}^{2-\alpha} \Theta_{tot}, \tag{15}$$

$$\Theta_{tot} = \sqrt{\frac{0.15}{\Omega_m h^2}} \left(\frac{0.02}{\Omega_b h^2} \right) \Theta_X \Theta_\tau(z)$$

For the models under discussion, it can be expected that the function $\Theta_\tau(z) \sim const. \geq 1$ and $\varepsilon(z) \propto (1+z)^{-1}$ at least up to $z \sim 10$ instead of the $\varepsilon = const.$ considered in [18].

For a given $\varepsilon(z)$, the power spectra of CMB anisotropy, polarization and their cross-correlation can be found with the modified CMBFAST code. Here we consider the cosmological model with $\Omega_b h^2 = 0.02$, $\Omega_m = 0.3$, $\Omega_\lambda = 0.653$, $h = 0.65$ and the Harrison-Zel'dovich primordial power spectrum of initial adiabatic perturbations ($n = 1$) without a contribution of gravitation waves and a later reionization.

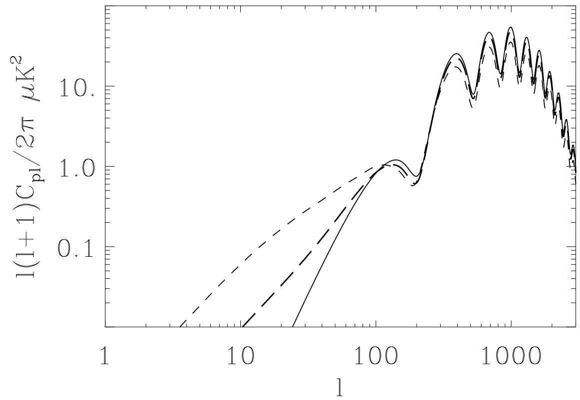

FIG. 2. The CMB polarization vs. l for $\varepsilon = 0$ (solid line), $\varepsilon_H = 2/(1+z)$ (dashed line) and $\varepsilon_H = 3/(1+z)$ (long dashed line).

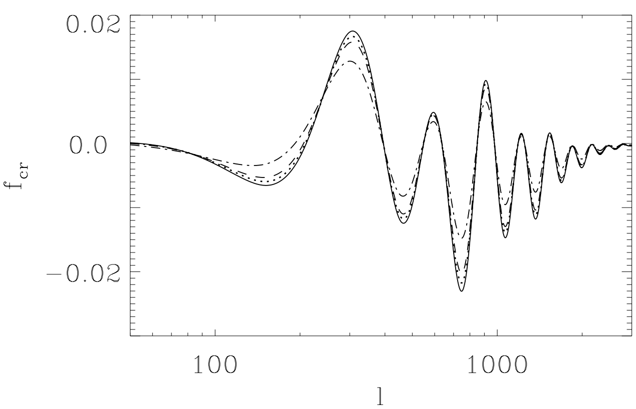

FIG. 3. The cross-correlation function of anisotropy and polarization for the same three values of ε.

For the standard model with $\varepsilon = 0$ and for two models with $\varepsilon(z) = 2/(1+z)$ & $3/(1+z)$, the power spectra of anisotropy and polarization, $l(l+1)C(l)/2\pi$ and $l(l+1)C_{pl}(l)/2\pi$, are plotted in Figs. 1, 2. In Fig. 3 the cross correlation of anisotropy and polarization is also presented.

As is seen from Fig. 1, the power spectrum of anisotropy is very sensitive to the influence of additional UV background that in turn restricts the intensity of UV radiation and the mass and life–time of X-particles, M_X & τ_X or Θ_τ, and the spectral index, α. Thus, this influence becomes negligible for $\varepsilon \leq (1+z)^{-1}$ while for $\varepsilon \geq 3/(1+z)$ both the delay of the hydrogen recombination at $z \sim 10^3$ and the CMB scattering at less redshifts result in an essential suppression of all Doppler peaks. For $\varepsilon \sim 2/(1+z)$, the expected power spectrum is well consistent with available observational data [1,2].

V. THE HYDROGEN IONIZATION HISTORY

At redshifts $z \ll 10^3$ the degree of ionization of hydrogen is small, all Ly–c photons are rapidly absorbed, and the fraction of ionized hydrogen atoms can be roughly estimated from the equilibrium equation which describes the conservation of number of electrons and Ly–c photons together,

$$\frac{dx_H}{dt} = \alpha^*_{rec}\langle n_b\rangle(1-x_h)^2 - x_H\varepsilon H(z) = 0 \qquad (16)$$

$$\alpha^*_{rec} \simeq 4{\cdot}10^{-13}\left(\frac{T}{10^4K}\right)^{-0.62}\frac{cm^3}{s},\ T\approx 300K\left(\frac{1+z}{100}\right)^2.$$

Here x_H is the fraction of neutral hydrogen, α^*_{rec} is the recombination coefficient for states with the principle quantum number $n \geq 2$, T is the temperature of hydrogen under the condition of small ionization at $(1+z)\leq 100$ and $\langle n_b\rangle$ is the mean number density of baryons (14). For simplicity, we neglected here the contribution of helium. Numerically, we have from (16)

$$(1-x_H)^2 \simeq \frac{\varepsilon H(z)}{\alpha^*_{rec}n_b} \sim 10^{-4}\varepsilon(0)\left(\frac{100}{1+z}\right)^{5/4}\Theta_{tot}, \quad (17)$$

that essentially exceeds the standard estimates of 'frozen' ionization degree $1-x_H \sim 10^{-3}$ [18].

For a given $\varepsilon(z)$, the ionization history can be restored more accurately with the modified RECFAST code [19]. In Fig 4. the fraction of ionized hydrogen, $1-x_H$, is plotted versus redshift for four different values of ε.

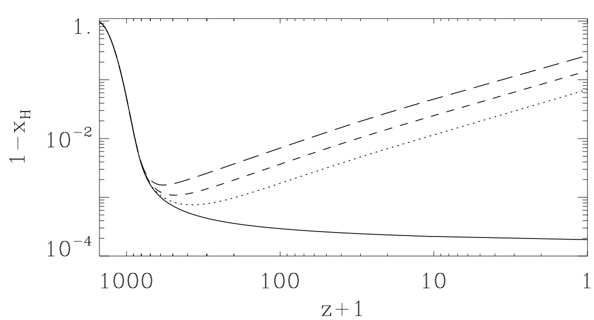

FIG. 4. The fractions of ionized hydrogen, $1-x_H$, vs. $1+z$ are plotted for $\varepsilon = 0$ (solid line), $\varepsilon = 0.3/(1+z)$ (dot line), $\varepsilon = 1/(1+z)$ (dashed line), and $\varepsilon = 3/(1+z)$ (long dashed line).

The residual fraction of ionized hydrogen, $1-x_H$, drops up to $\sim 10^{-3}$ at redshifts $z \sim 600-200$ and progressively increases at $z \leq 50$ up to $1-x_H \to 0.01-0.1$. Even for $\varepsilon = 0.3/(1+z)$ when the distortion of recombination is negligible, the reionization of hydrogen at $z \leq 50$ exceeds the standard one of about of $5-10$ times that essentially accelerates the formation of molecules H_2 and first stars. At the same time, these results indicate that the UV flux generated by decays of X–particles is small as compared with the flux

$$J \approx (1\pm 0.5)\cdot 10^{-21} erg\ cm^{-2}s^{-1}st^{-1}Hz^{-1}, \qquad (18)$$

actually observed [20] at $E = I_H$ and $z \sim 3$.

VI. SUMMARY AND DISCUSSION

In the paper we consider the observational consequence of the energy injection due to possible decays of SHDM particles. As was noted in Introduction, many kinds of such particles are now discussed, in particular, in context of production of UHECRs (see, e.g., [8–10]).

We show that the energy of decay is transformed to UV range with a reasonable efficiency $\kappa \approx 10^{-5}$ (13) that, for suitable mass and rate of decay of SHDM particles, delays the hydrogen recombination and provides the observed distortions of the CMB anisotropy. The action of this factor must be taken into account in interpretation of measured anisotropy together with usually considered main cosmological parameters.

We show that the action of the same decays can increase of about $5-10$ times the degree of hydrogen ionization at redshifts $z \leq 50$ and accelerate the formation of H_2 molecules and first stars during "dark ages".

Here we do not specify the kind of SHDM particles and their properties as for the small life – time the concentration of such particles at $z = 0$ can be small and they cannot be detected as UHECRs. Non the less, if their life – time is sufficiently large and their concentration at $z = 0$ is still essential then such particles can be linked to some fraction of observed UHECRs and their properties can be specified using the observational information about the UHECRs (see detailed discussion in [8]).

In particular, the upper limit of $\varepsilon(z) \leq 3/(1+z)$ allows to link the mass of the X-particle with their life – time and the power index of the spectrum of decay. For $E_{obs} = 10^{11}$GeV and $\lg\Theta_X \approx 4.7(1.5-\alpha)$ [8], the expression (15) can be rewritten as follows:

$$\alpha \approx 2 - \frac{6.35 + \lg(\varepsilon(0)/3) - \lg\Theta^*_{tot}}{4.7+\lg(M_{16})}, \qquad (19)$$

$$\Theta^*_{tot} = \Theta_\tau\sqrt{\frac{0.15}{\Omega_m h^2}\frac{0.02}{\Omega_b h^2}\frac{\Theta_X}{10^{4.7(\alpha-1.5)}}}$$

For four values ε and $\Theta^*_{tot} = 1$, the function $\alpha(M_X)$ is plotted in Fig. 5. This Fig. demonstrates that values $\alpha \leq 1$ is consistent with observational restrictions only for $M_X \leq 10^{17}$GeV and/or $\Theta^*_{tot} \leq 1$. On the other hand, for the most popular value $\alpha \sim 1.5$ the measurable distortions of power spectrum of CMB anisotropy appear for

$$\Theta^*_{tot} \approx 10^4/\sqrt{M_{16}} \qquad (20)$$

and for $\Theta^*_{tot} = \Theta_\tau \approx \exp(t_u/\tau_X)$ we get for the threshold life–time, τ_X,

$$t_u/\tau_X \approx 9.2 - 0.5\ln(M_{16}) \qquad (21)$$

that implies a significant evolution of the rate of decays even for the masses $M_{16} \sim 10^3$, $M_X \sim 10^{19}$GeV.

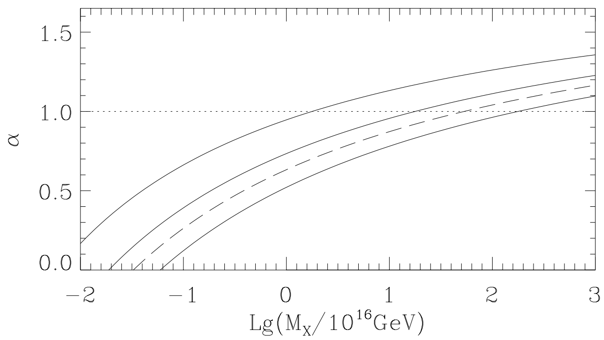

FIG. 5. The spectral index, α, vs. the mass of decaying X-particle, M_X, plotted for $\Theta^*_{tot} = 1$ and $\varepsilon = 10/(1+z)$, $1/(1+z)$, & $0.1/(1+z)$ (solid lines), and $\varepsilon = 3/(1+z)$ (long dashed line).

For other kinds of discussed SHDM particles with $\Theta_\tau = (t_u/t)^{p-1}$ estimates (20) show that they concentration at $z = 10^3, \Theta_\tau \sim 10^{4.5(p-2)}$ crucially depends upon the exponent p and instead of (21) we get for the threshold exponent

$$p \approx 2.9 - 0.1\,\mathrm{lg}(M_{16}) \qquad (22)$$

These estimates demonstrate that the observations of power spectrum of CMB anisotropy can be used to restrict the possible properties of the SHDM particles.

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